

Hidden Sector Particles at the LHC

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“Snowmass” Workshop
Minneapolis, MN

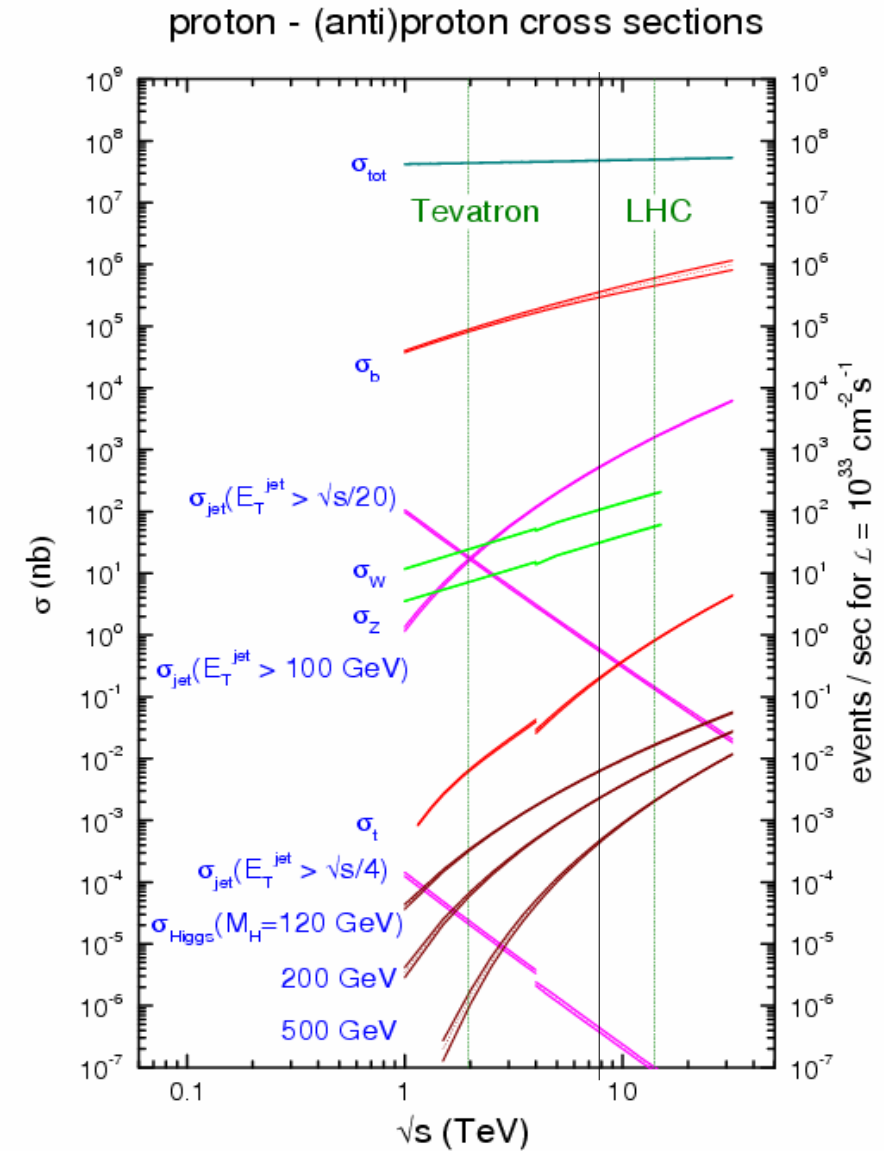
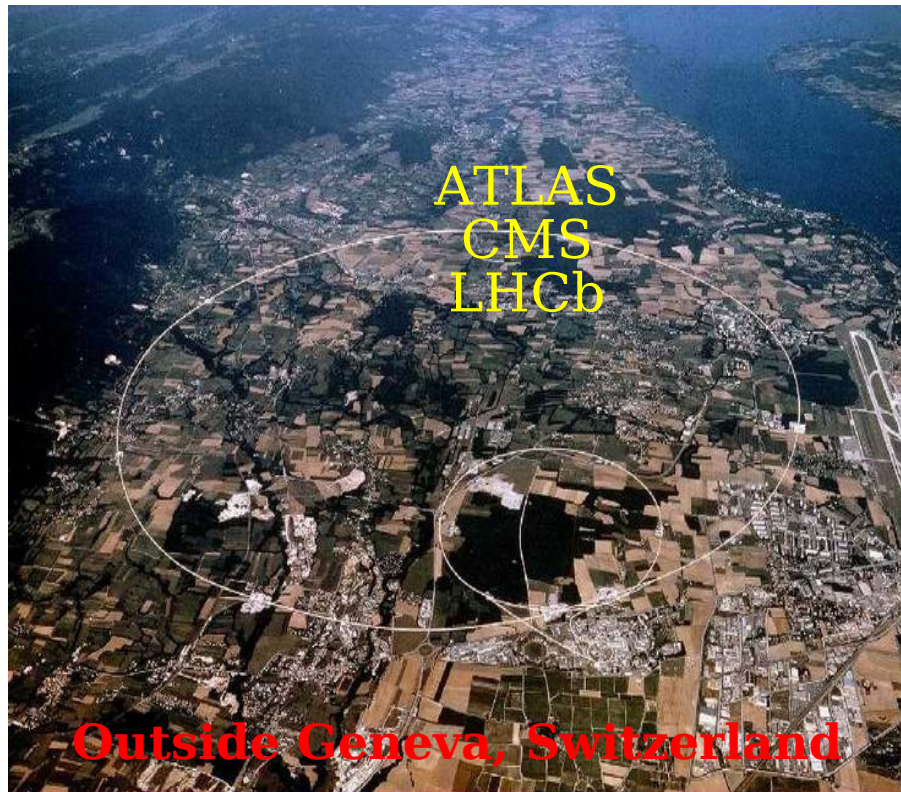
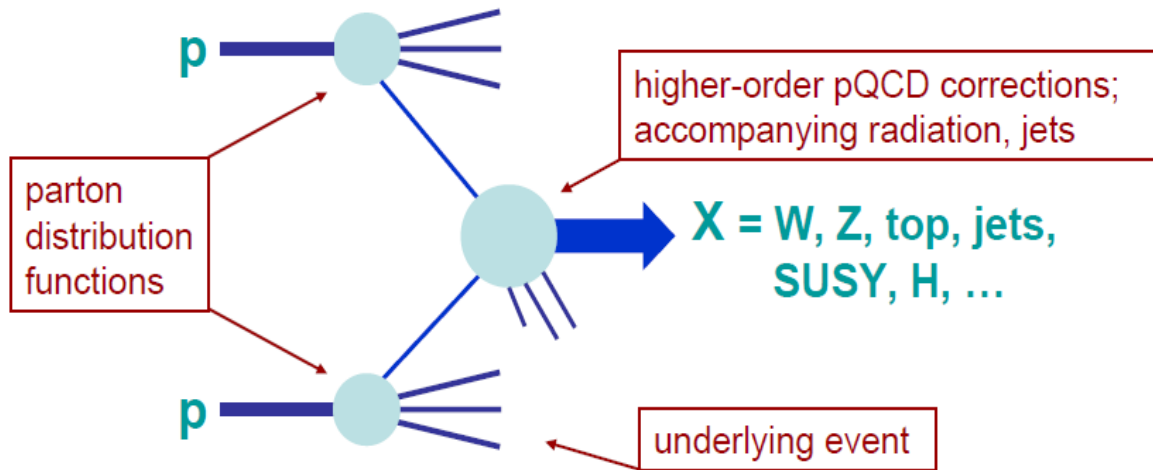
July 31, 2013

<https://indico.fnal.gov/contributionDisplay.py?contribId=425&sessionId=43&confId=6890>



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The (intense) energy frontier

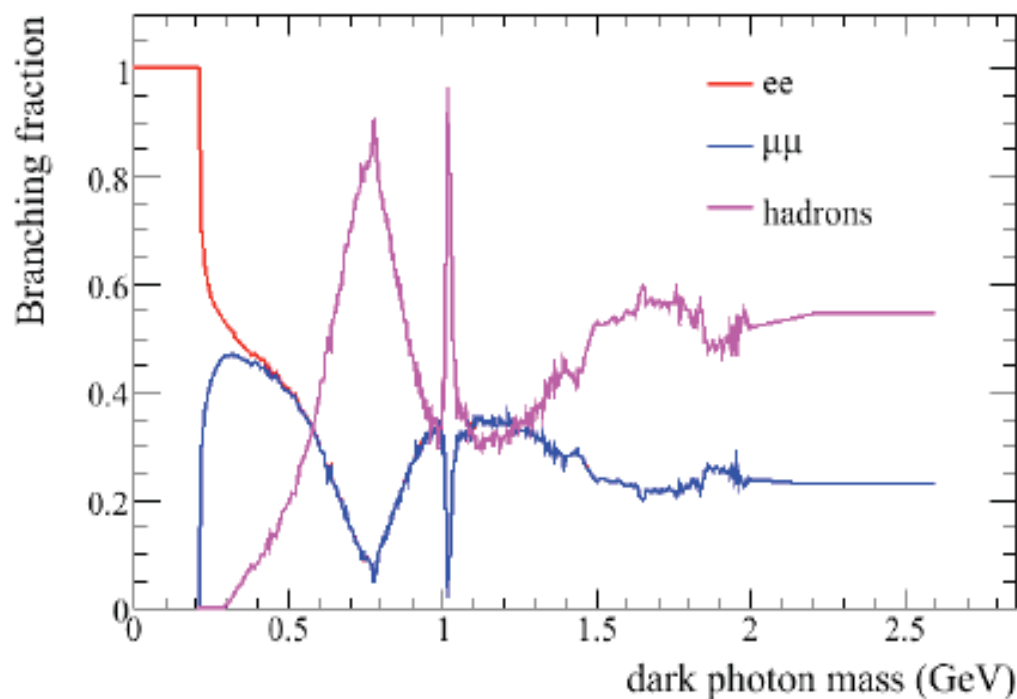
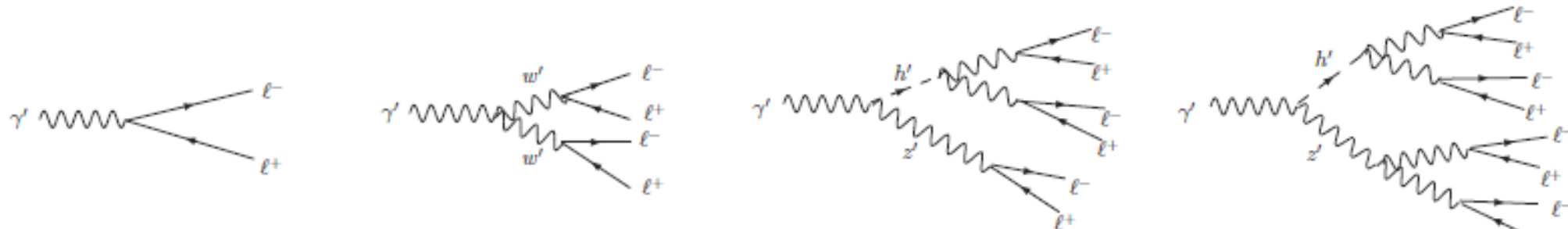


$\sim 150 \text{ Hz}$ of $Z \rightarrow$ "Giga Z"
 $\sim 0.03 \text{ Hz}$ of $H \rightarrow$ "Mega H"

Lepton jets

- **Dark photons are *boosted***

Create “lepton jets”:
pairs of collinear electrons or muons



Probably prompt decays,
but maybe not...

$$c\tau_{2\text{-body}}^{\gamma' \rightarrow n\ell} \sim \frac{1}{\alpha\epsilon^2 m_{\gamma'}} = 2.7 \times 10^{-6} \text{ cm} \left(\frac{\text{GeV}}{m_{\gamma'}} \right) \left(\frac{10^{-3}}{\epsilon} \right)^2$$

SUSY lepton jets

- LSP decays to dark sector?!**

BR = 1!

Prompt:

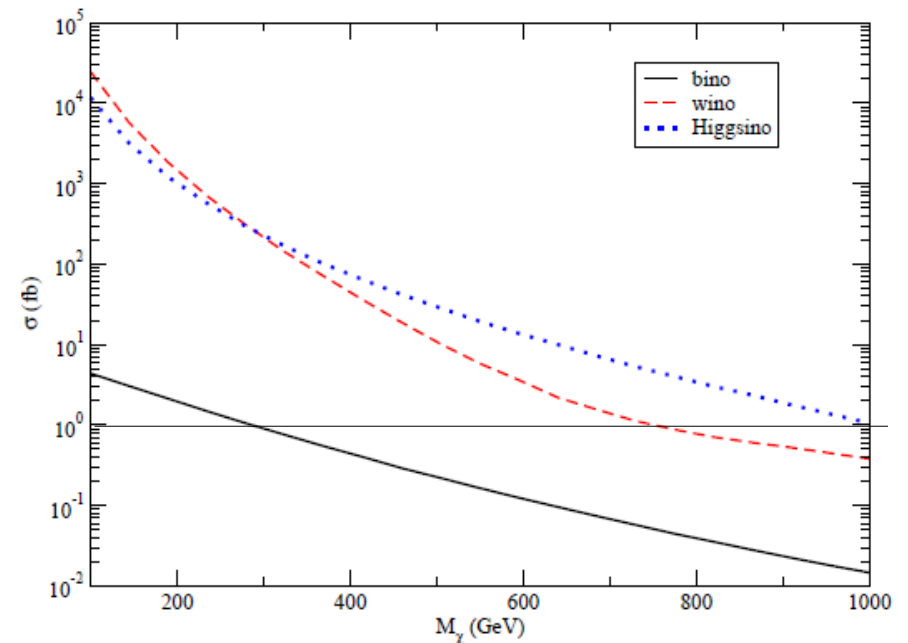
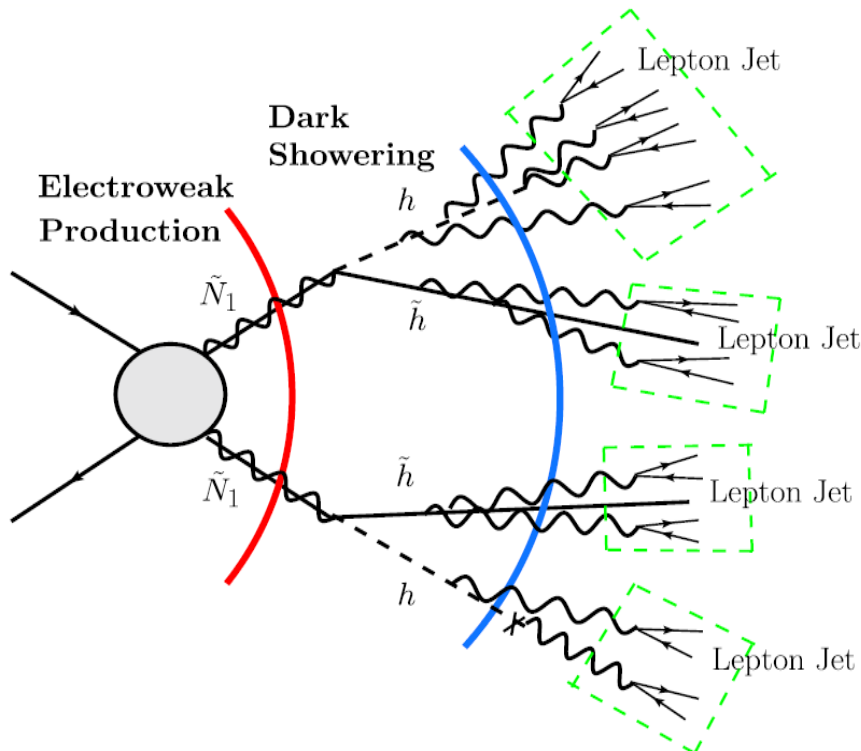
- Changes signature of SUSY**

- Less MET
- Two *dark* photons (lepton jets)

$$\tau_{\text{LSP} \rightarrow h + \tilde{h}} \sim \left(\alpha_y^{\text{dark}} f_{\tilde{B}}^2 \epsilon^2 M_{\text{LSP}} \right)^{-1}$$

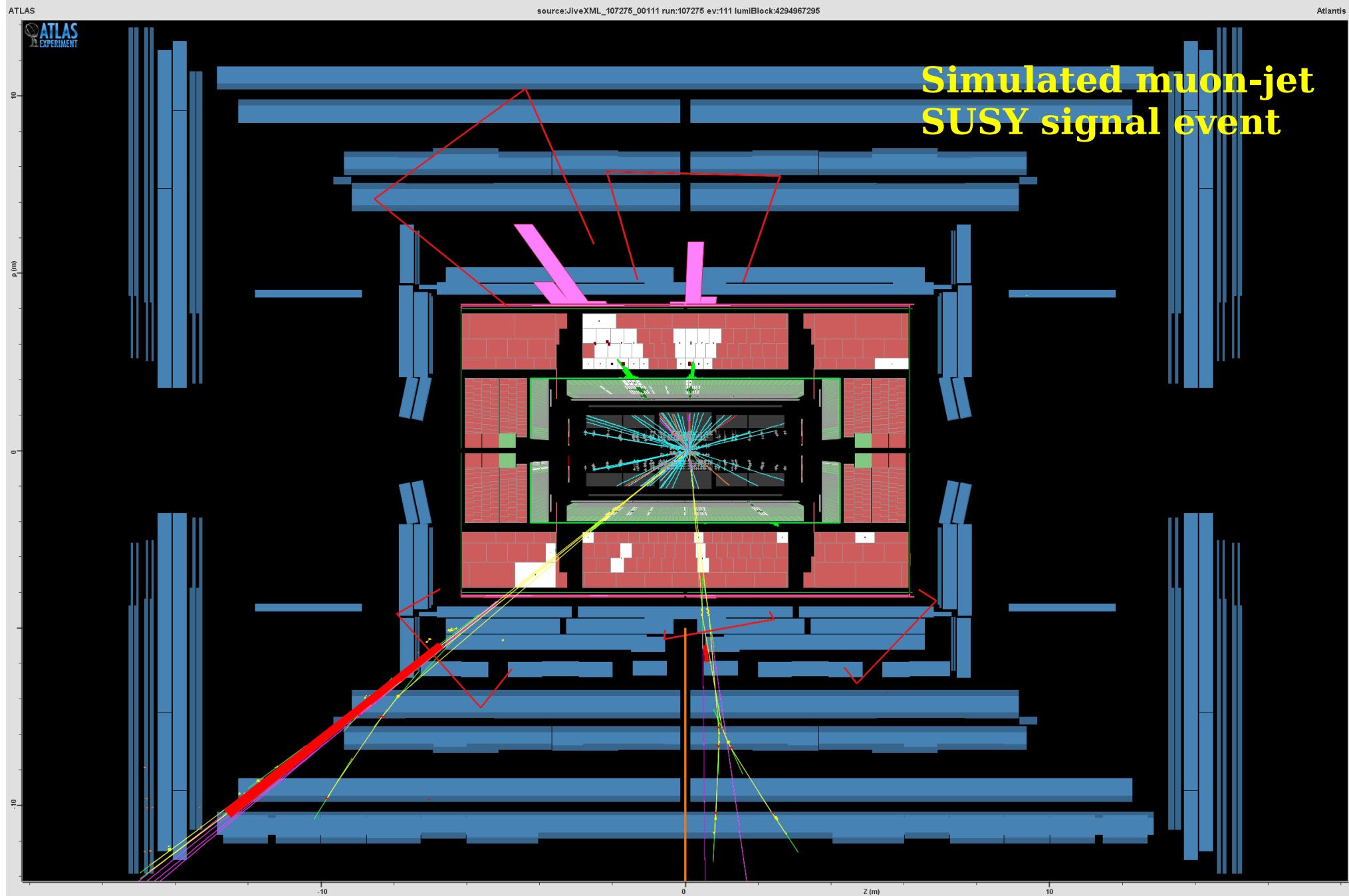
$$= 7 \times 10^{-19} \text{ s} \left(\frac{100 \text{ GeV}}{M_{\text{LSP}}} \right)^2 \left(\frac{0.01}{\alpha_y^{\text{dark}}} \right) \left(\frac{1.0}{f_{\tilde{B}}} \right)^2 \left(\frac{10^{-3}}{\epsilon} \right)^2$$

Electroweak production is small but still observable



Possibly large production rate for colored SUSY particles...

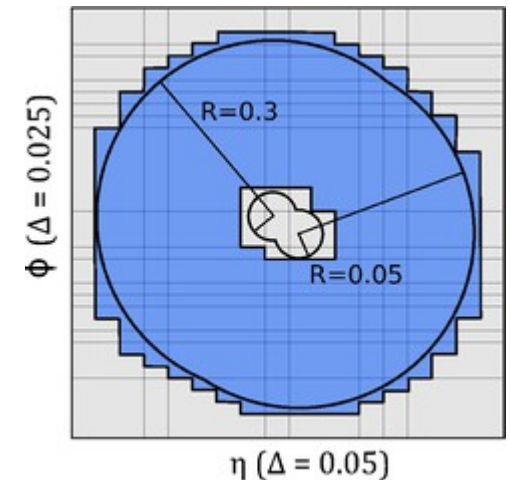
SUSY lepton jets at ATLAS



SUSY lepton jets at ATLAS

- Search for events with:
 - 2 prompt muon lepton-jets
 - 2 prompt electron lepton-jets
 - 1 prompt 4-muon lepton-jet
- Custom lepton-jet identification to separate from QCD jets
- Backgrounds measured in control regions
- Dark photon also *could* give peak at dark photon mass
- No excess observed

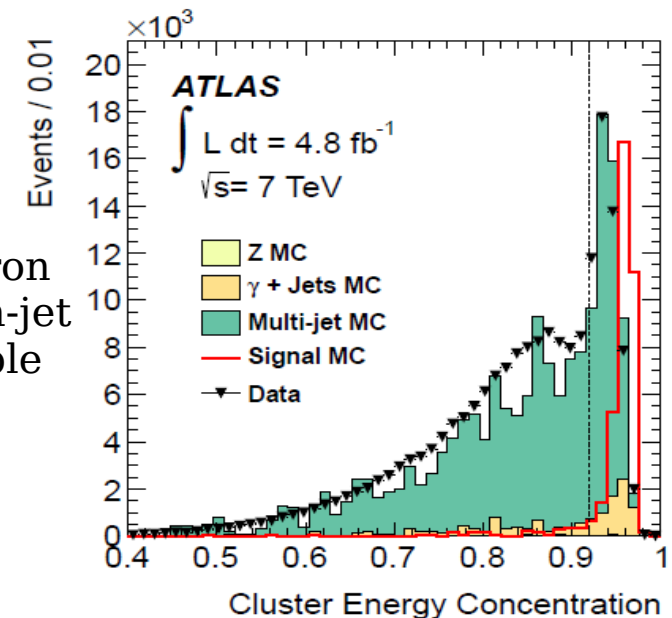
Muon isolation definition



	Electron LJ	1 Muon LJ	2 Muon LJ
Data	15	7	3
All background	15.2 ± 2.7	3.0 ± 1.0	0.5 ± 0.3

Jet prob bkgd method: $14.55^{+0.23}_{-0.04}$ 2.2 ± 0.9 events

Electron lepton-jet variable



SUSY lepton jets at ATLAS

- Cross-sections excluded for various dark-photon masses and radiation parameters $< \sim 0.02 - 0.1$ pb
- Constrains strong-production up to \sim TeV and even weak-production up to ~ 400 GeV (assuming LSP \rightarrow lepton-jet)

Cross-section limits for various decays

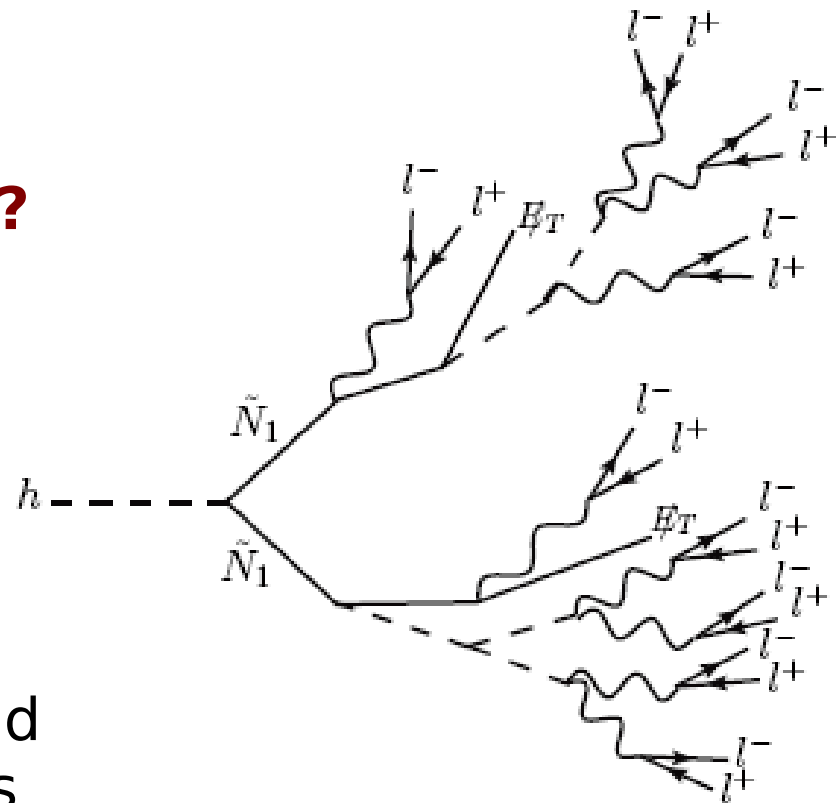
Signal Parameters α_d m_{γ_D} [MeV]		Electron LJ Obs (Exp) pb	1 Muon LJ Obs (Exp) pb	2 Muon LJ Obs (Exp) pb
0.0	150	0.082 (0.082)	-	-
0.0	300	0.11 (0.11)	0.060 (0.035)	0.017 (0.011)
0.0	500	0.20 (0.21)	0.15 (0.090)	0.019 (0.012)
0.10	150	0.096 (0.10)	-	-
0.10	300	0.37 (0.37)	0.064 (0.036)	0.018 (0.011)
0.10	500	0.39 (0.39)	0.053 (0.035)	0.018 (0.011)
0.30	150	0.11 (0.11)	-	-
0.30	300	0.40 (0.40)	0.099 (0.055)	0.020 (0.012)
0.30	500	1.2 (1.2)	0.066 (0.043)	0.022 (0.015)

<http://arxiv.org/abs/1212.5409>

- **Update to 2012 data**
- **Study *long-lived* decays to electron (or muon?) lepton-jets in the tracker ($\sim 0.1 - 10$ cm)**

Higgs decays

- The Higgs exists!
- **Higgs decays to dark sector??**

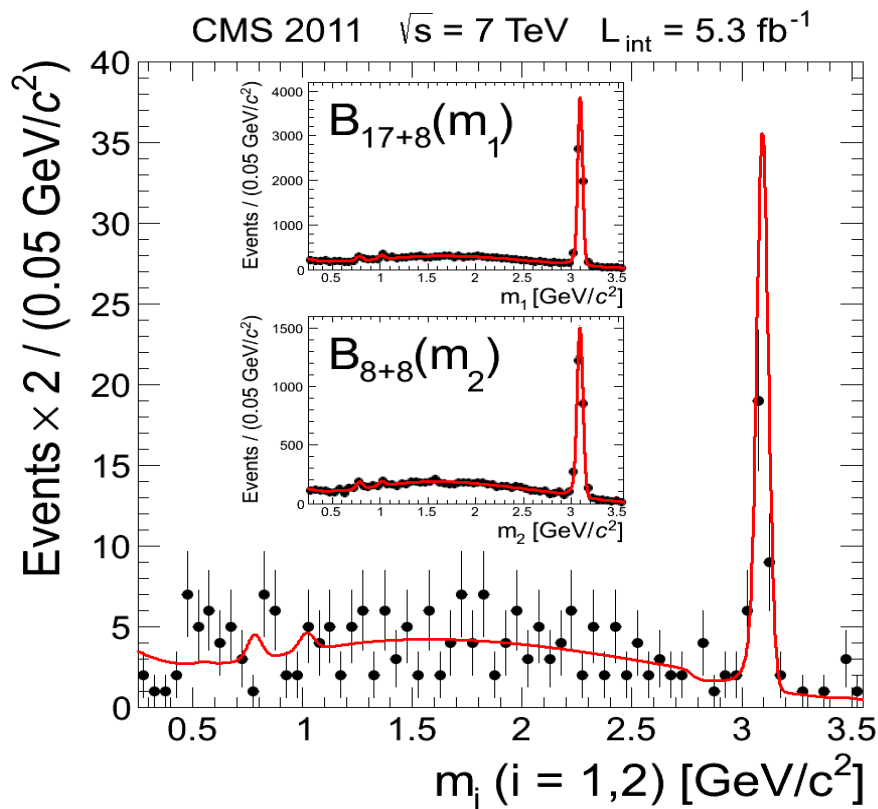


- Since it has a small width, it could have a large BR to non-SM states

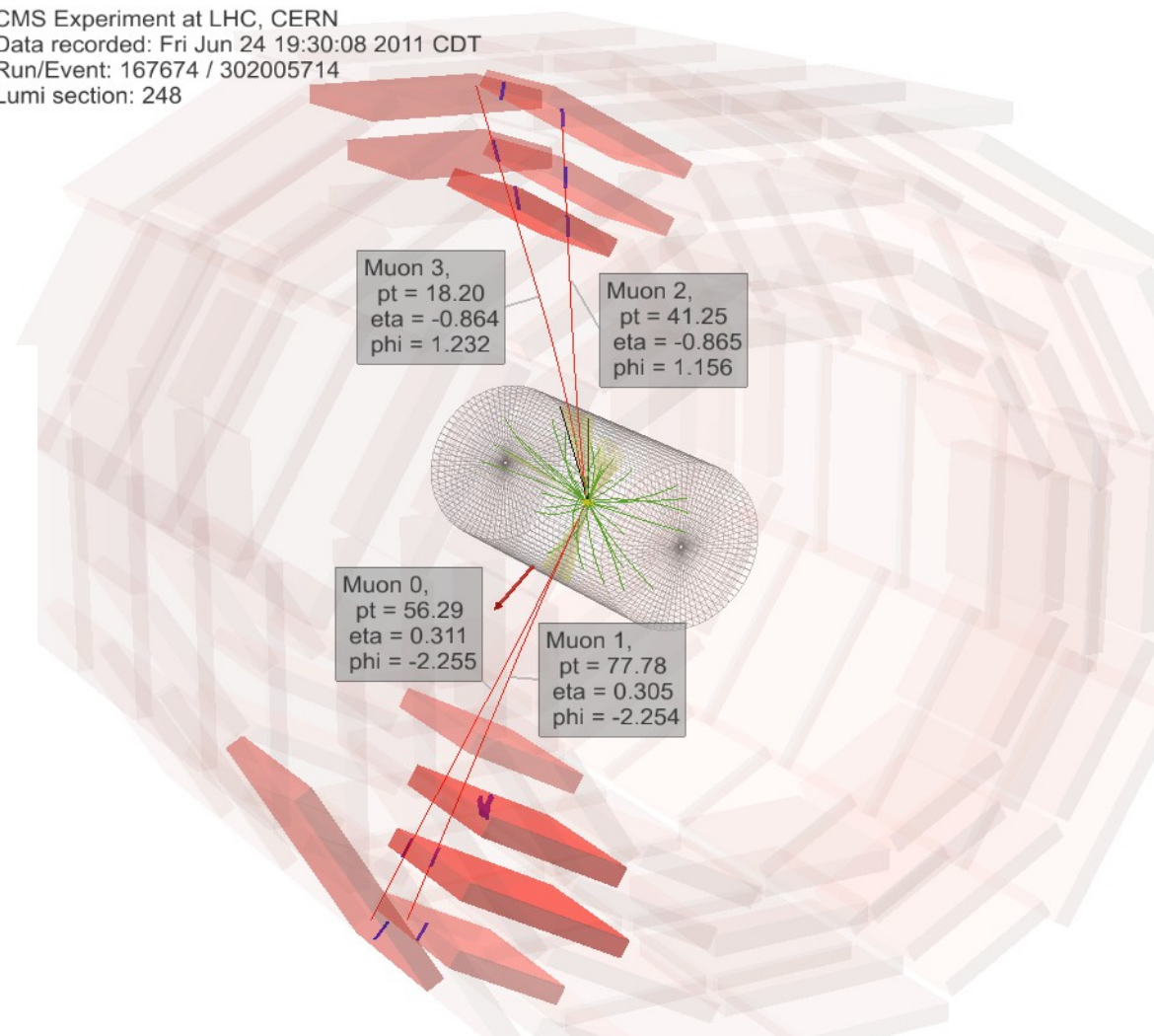
Branching ratio could be $O(10\%)$!

CMS search for $H \rightarrow \text{muon-jets}$

- Select 4-muon events
- Look for di-muon invariant mass bump at low mass in *isolated* muon pairs



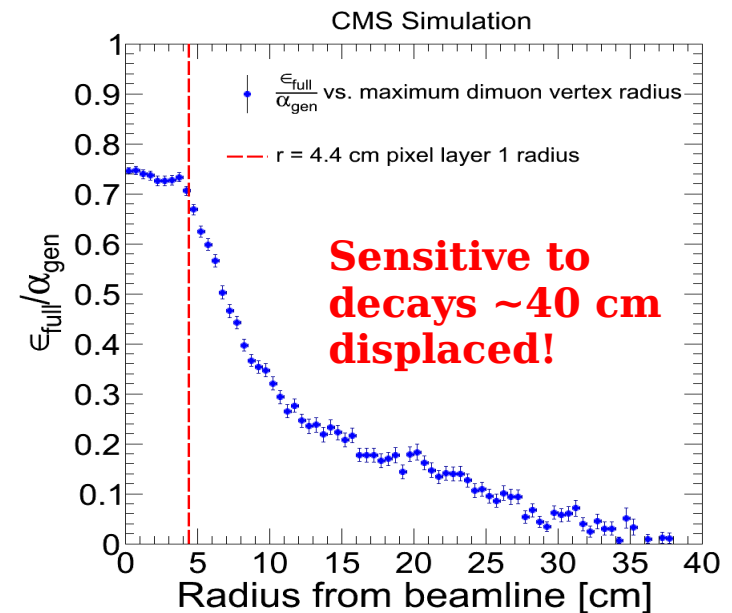
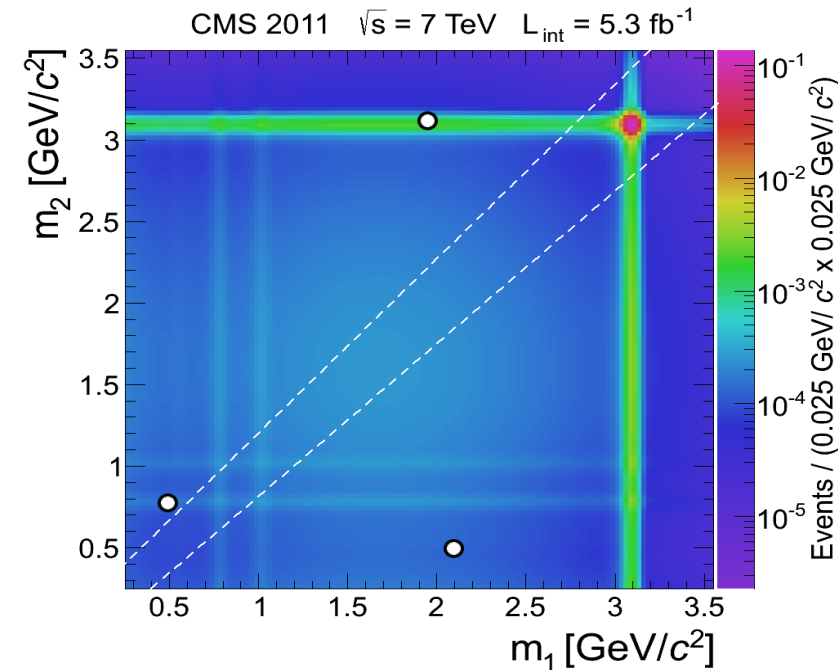
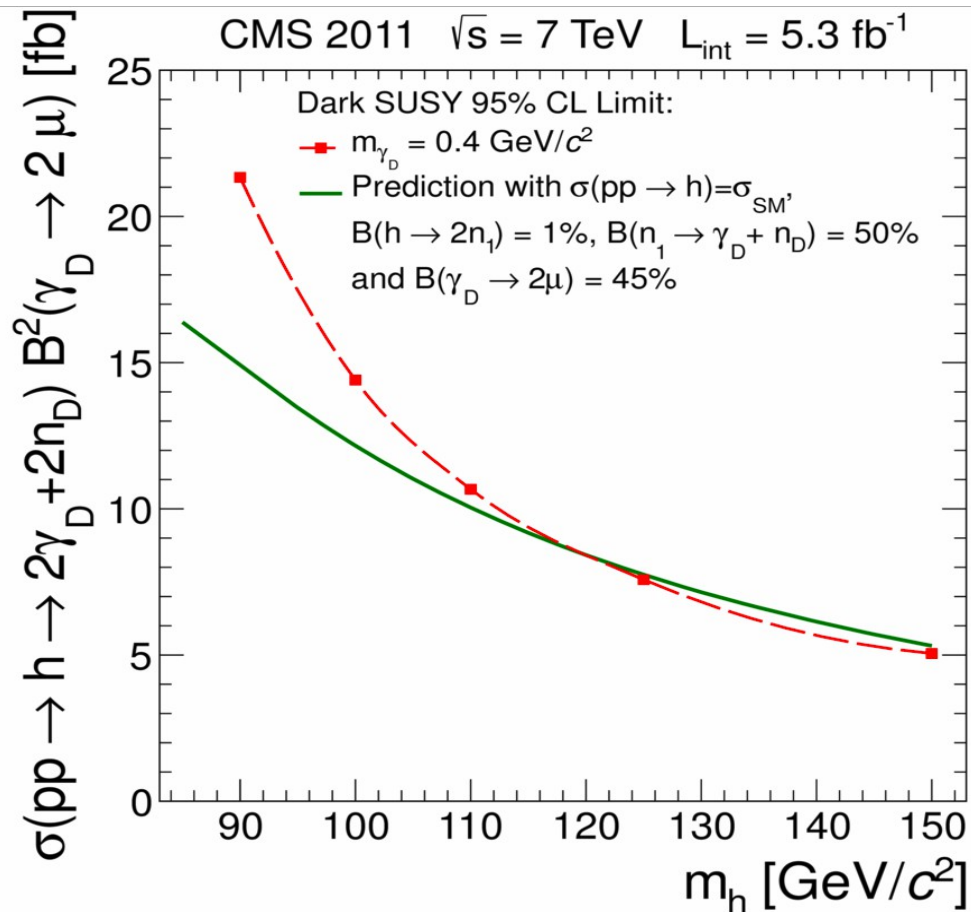
CMS Experiment at LHC, CERN
Data recorded: Fri Jun 24 19:30:08 2011 CDT
Run/Event: 167674 / 302005714
Lumi section: 248



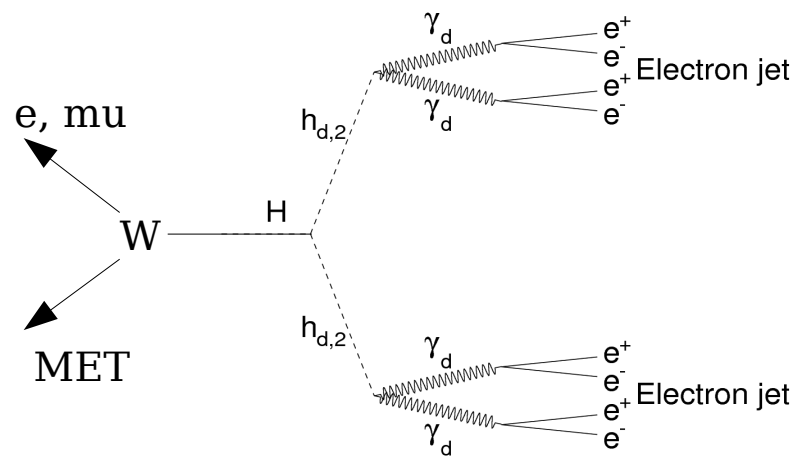
<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO12012>

CMS search for $H \rightarrow \text{muon-jets}$

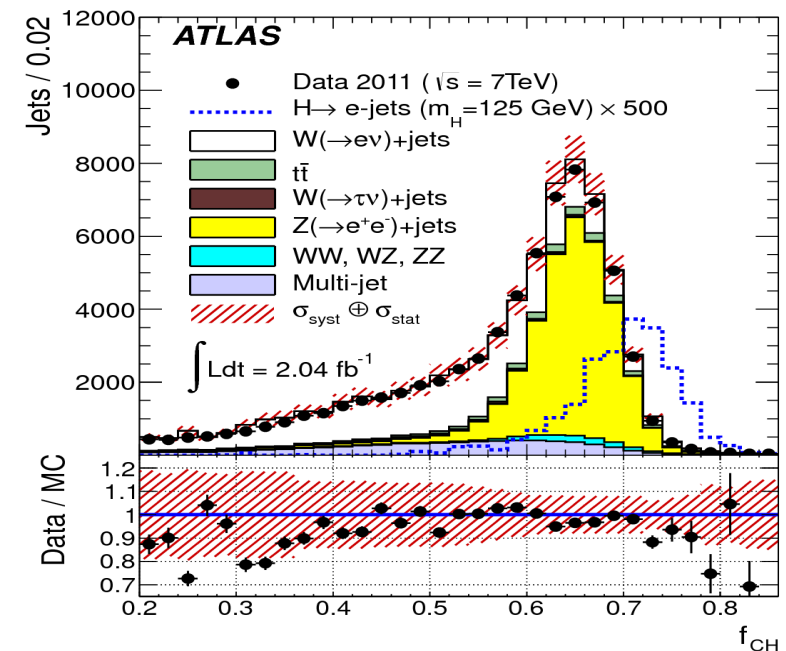
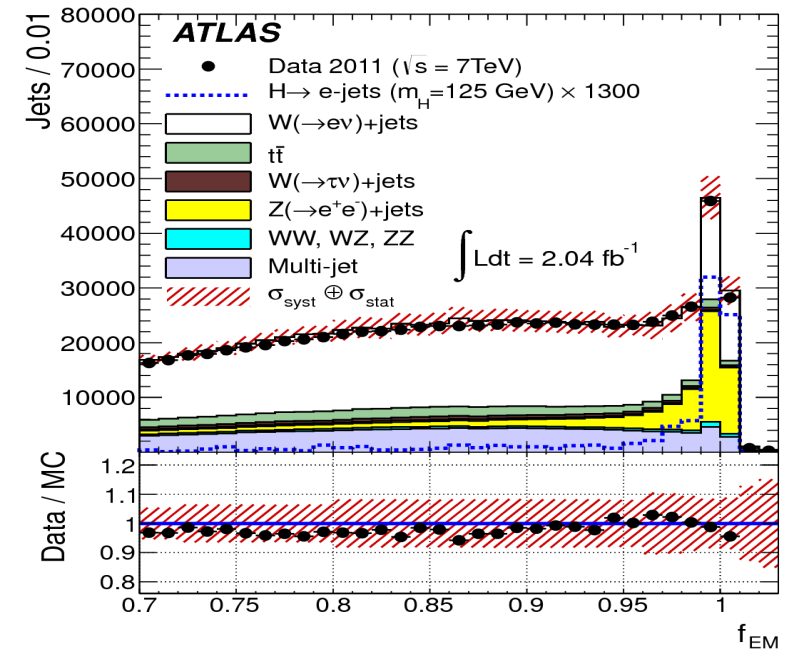
- Look for two $\mu^+ \mu^-$ pairs to have the same mass
- Exclude SM H decays with $\sim 1\%$ BR to muon-jets



ATLAS Search for $WH \rightarrow$ prompt electron-jets



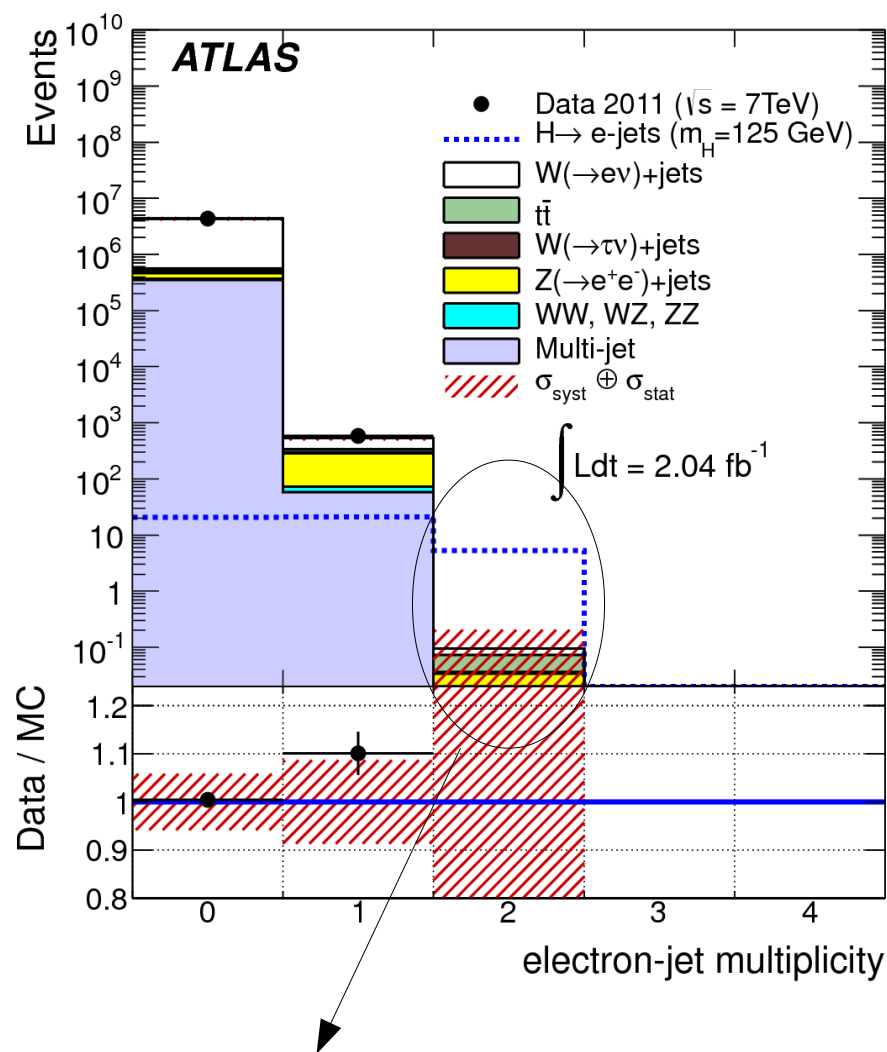
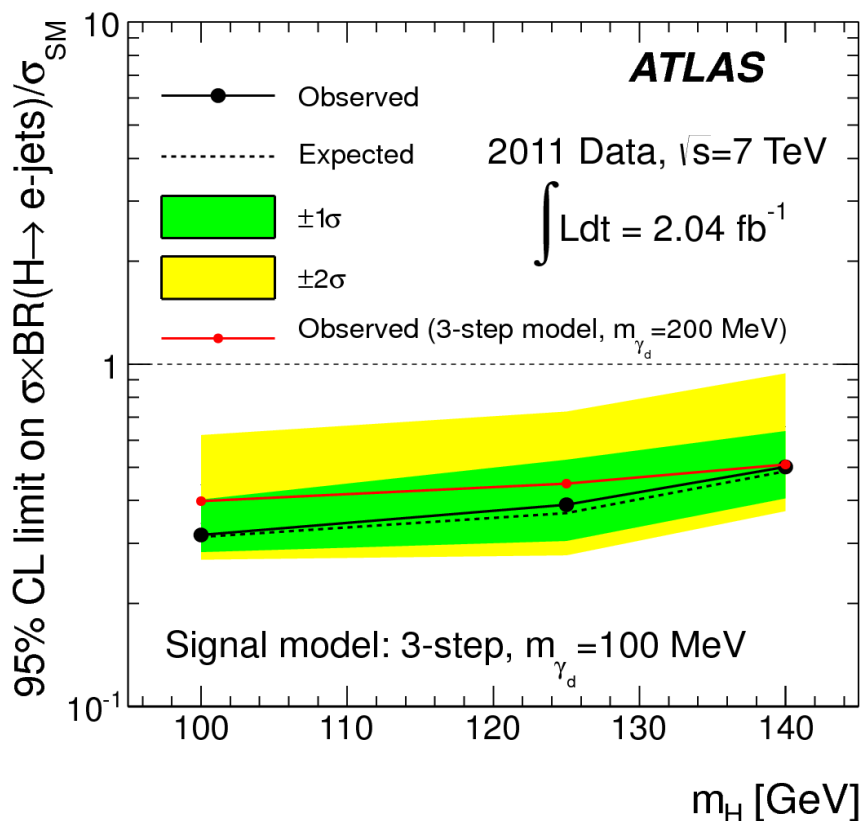
- Electron lepton-jets would have:
 - Large EM energy fraction
 - Large charged particle p_T fraction
 - Large number of tracks
- Separate signal from other backgrounds with QCD jets



ATLAS Search for $WH \rightarrow$ prompt electron-jets

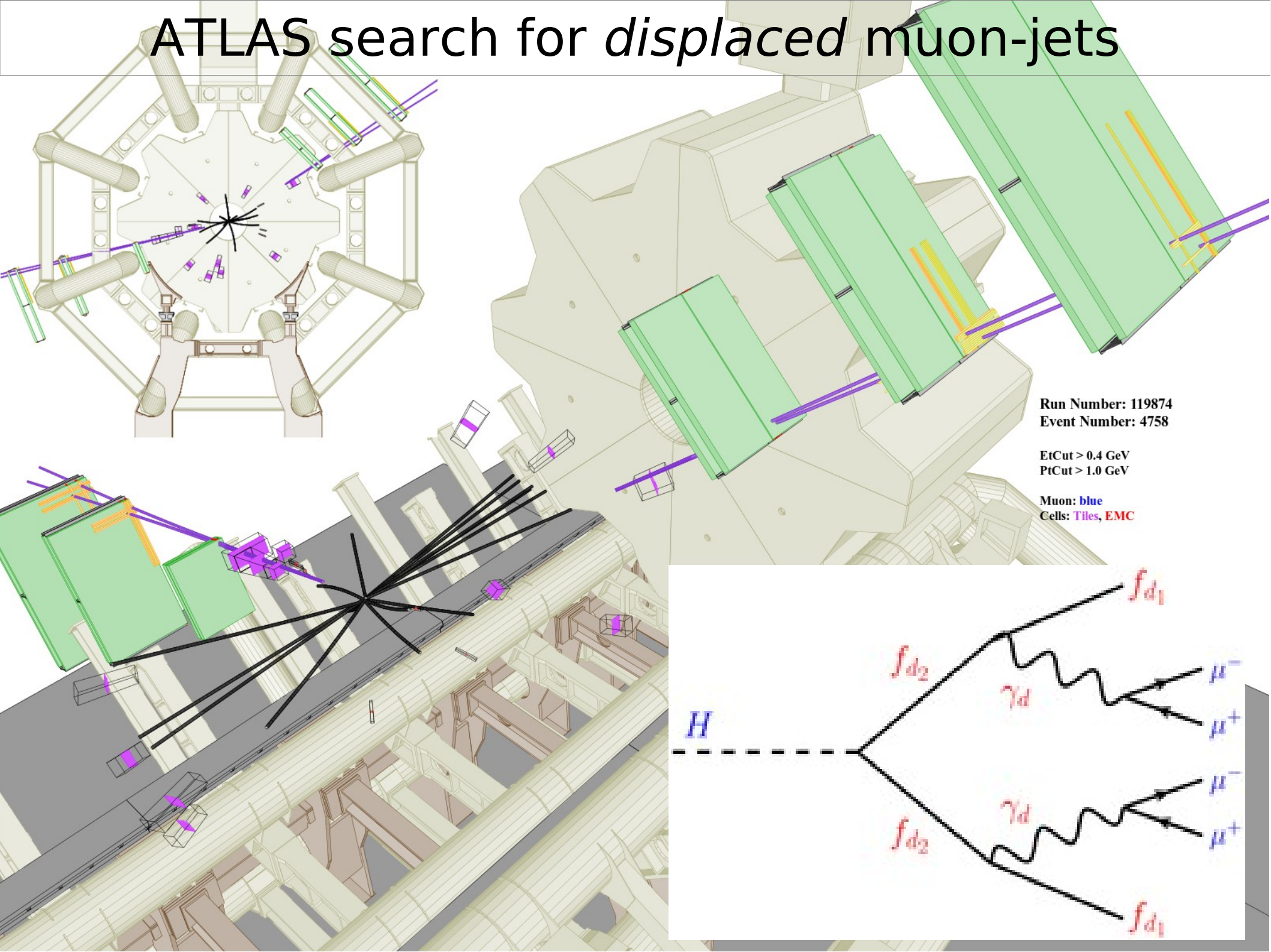
- No excess observed with 2 electron-jets
- $BR(h \rightarrow \text{electron-jets}) < \sim 50\%$**

<http://arxiv.org/abs/1302.4403>



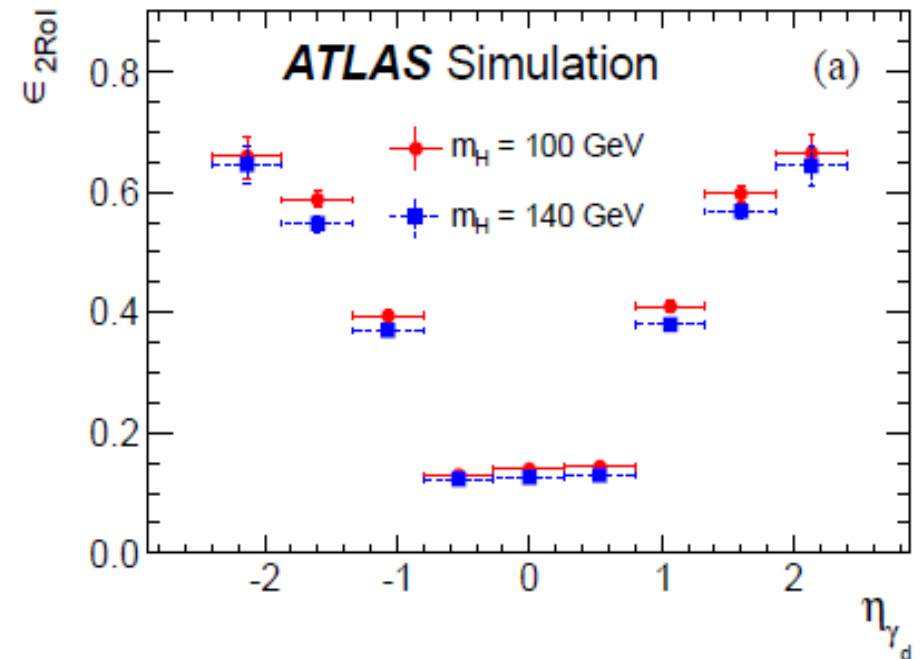
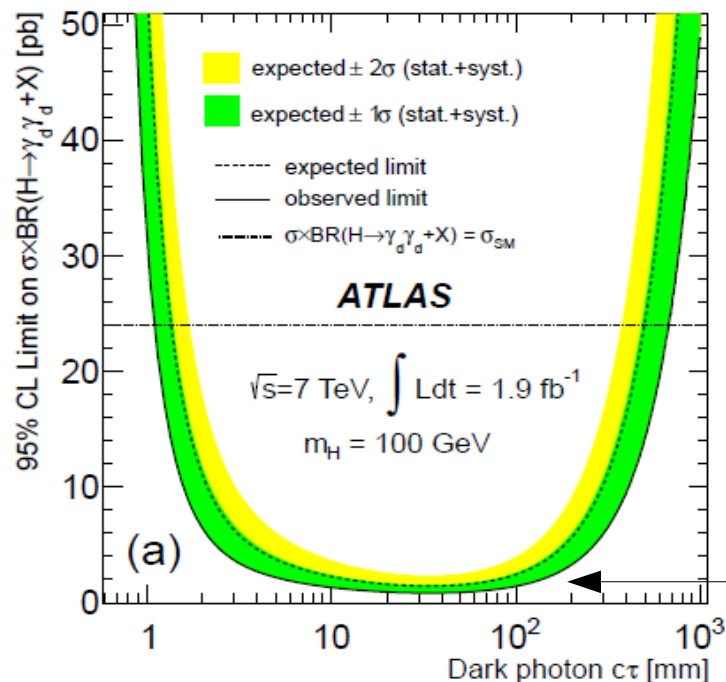
Backgrounds are small:
 20 fb^{-1} at 8 TeV $\rightarrow BR < \sim 5\%$

ATLAS search for *displaced* muon-jets



ATLAS search for *displaced* muon-jets

- Specially designed (software) trigger for multi-muon objects in the *muon system*
- No events observed with 2 isolated muon-jets
 - ~ 0.5 cosmic event expected



- Expanded analysis effort with 8 TeV data
 - Consider displaced decays to (b)jets \rightarrow *heavy dark photon*
 - Also use decays in the tracker or calorimeter

Already probing $\sim 10\%$ BR...
 Should reach $\sim 1\%$ BR with 20 fb^{-1}

Conclusions

- LHC could produce boosted dark photons → **lepton jets**
 - Decays of SUSY LSP or Higgs (or Z) are nice candidates
 - An important alternative way to search for a hidden sector
- Some initial LHC searches already complete
 - Decays to prompt electron lepton-jets (*working on displaced!*)
 - Decays to prompt, displaced, or very displaced muon lepton-jets
 - Constraining Higgs $BR \sim 10^{-1} - 10^{-2}$, Z $BR \sim 10^{-5} - 10^{-6}$!
- ATLAS and CMS will continue to search, in much larger datasets and at 13 TeV, starting in 2015
- With 300 fb^{-1} , exploring very interesting territory
 - Electroweak SUSY particles up to $\sim 1 \text{ TeV}$
 - Higgs $BR < \sim 10^{-3}$
 - Z $BR < \sim 10^{-7}$

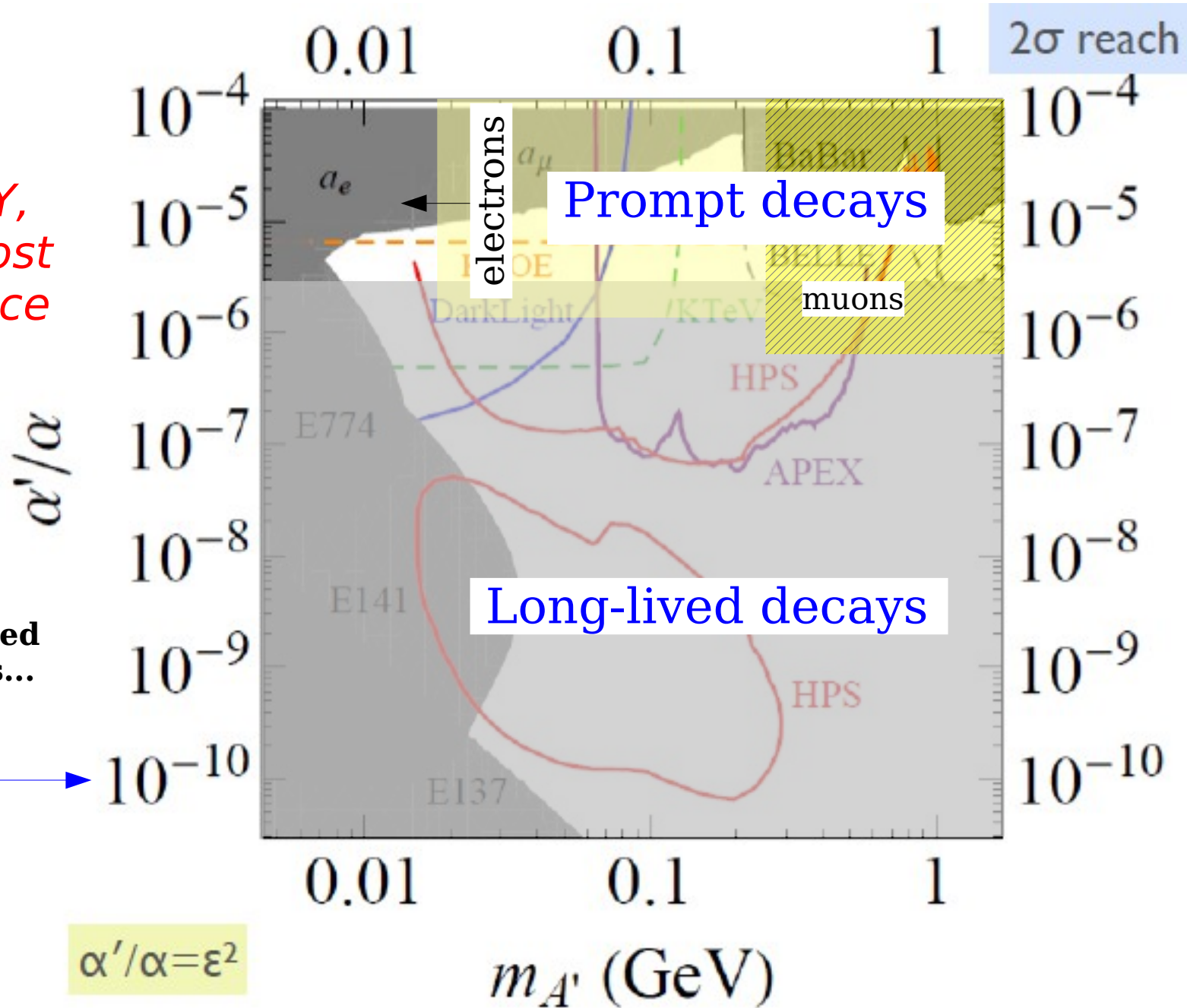
Backup

Constraints from the energy frontier

*With light SUSY,
sensitive to most
parameter space*

**Must study long-lived
dark photon decays...**

$c\tau \sim 30 \text{ cm}$ →

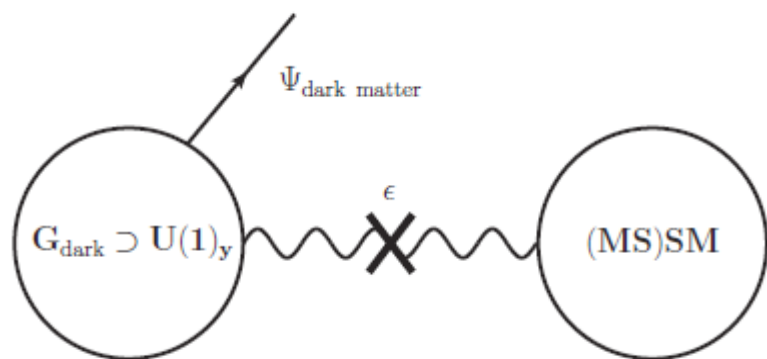


Dark-photon production

- Jet + dark-photon**

New, kinetically coupled U(1)

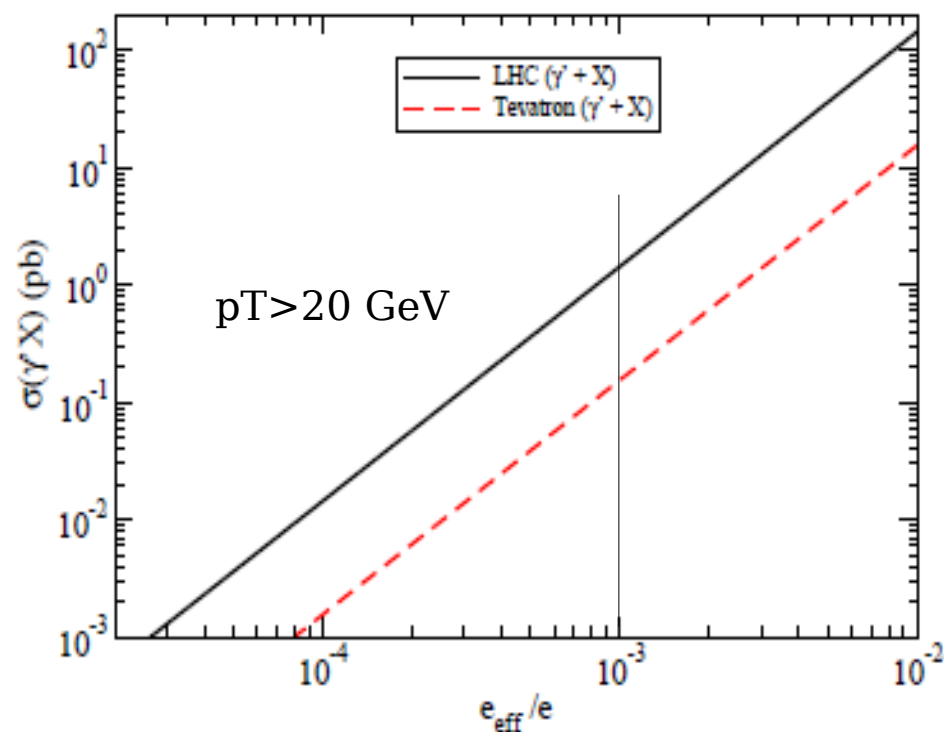
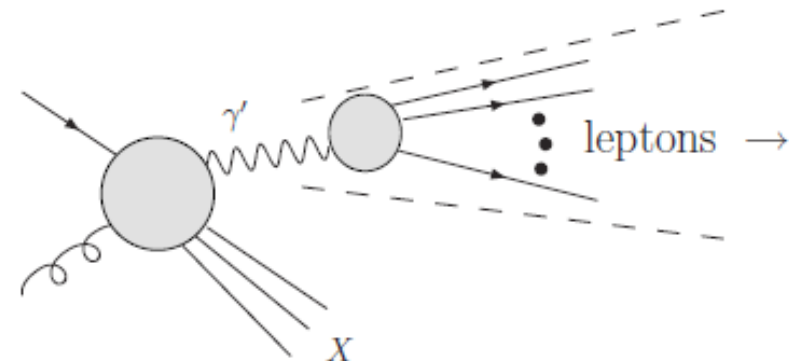
$$\mathcal{L}_{\text{gauge mix}} = -\frac{1}{2}\epsilon_1 b_{\mu\nu} A^{\mu\nu} - \frac{1}{2}\epsilon_2 b_{\mu\nu} Z^{\mu\nu}$$



$$\sigma \approx (\alpha_{\text{EM}} \epsilon)^2$$

Large jet background

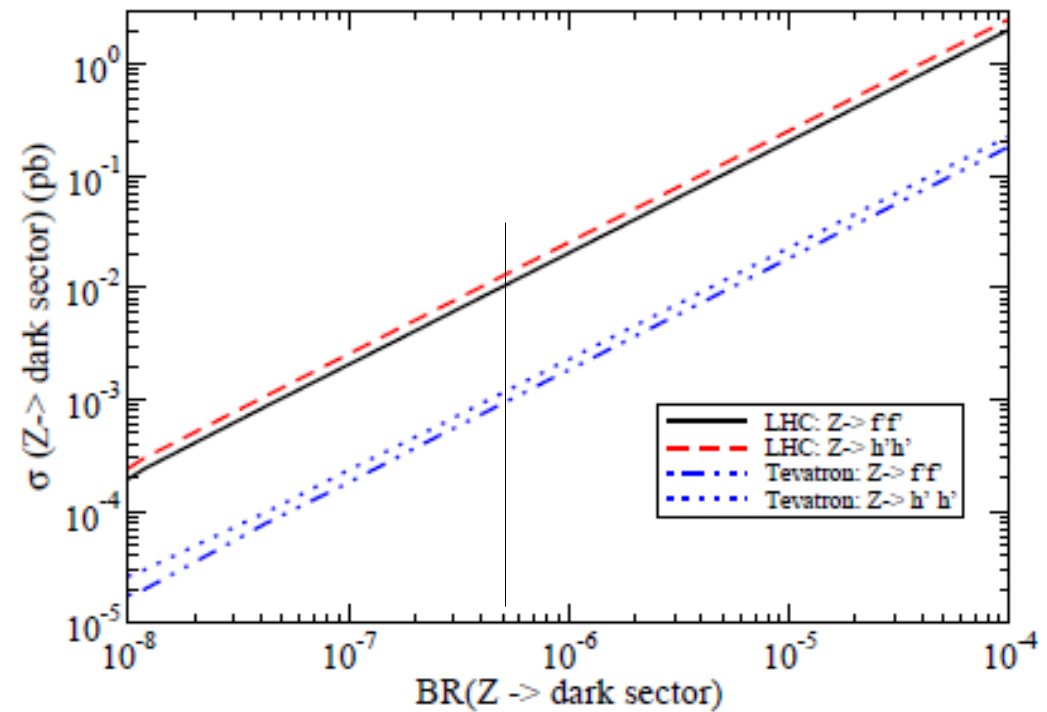
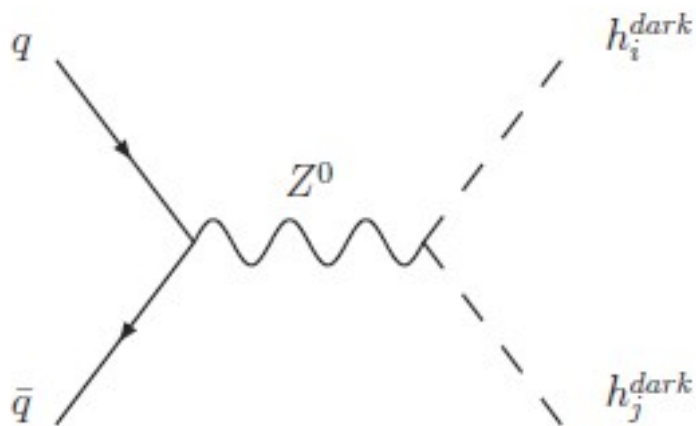
$$\sigma \approx (\alpha_s)^2$$



Rare Z decays

- Z decays to dark sector**

$$\text{BR}(Z^0 \rightarrow d_i d_i) = \frac{c_{d_i}}{\Gamma_Z^0} \frac{\epsilon^2 g_y^2 y_{d_i}^2 \sin^2 \theta_W}{48\pi} M_{Z^0}$$



Factor ~ 200 smaller cross-section
But *two* dark-things in each event

Much less background from jets